Multilayered Film Capacitors for Advanced Power Electronics and Electric Motors for Electric Traction Drives

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Project ID # EDT081

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Overview

Timeline

- Date: October 1, 2015
- End Date: September 29, 2017
- Percent Complete: 75%

Barriers

- Barriers addressed
  - Temperature performance: > 140 °C
  - Volume Reduction ~ 40%
  - Cost Reduction to $30

Budget

- Total project funding: $1750k
  - DOE share: $1400k
  - Contractor share: $350k
- Funding in FY 2016 - $ 735k
- Funding for FY 2017 - $ 600k
- Remaining: $ 415k (as of 2/28)

Partners

- SBE for capacitor development
- ORNL for capacitor characterization, cost modeling
- CWRU for materials development

SBE

Oak Ridge National Laboratory

Case Western Reserve University EST. 1826 think beyond the possible

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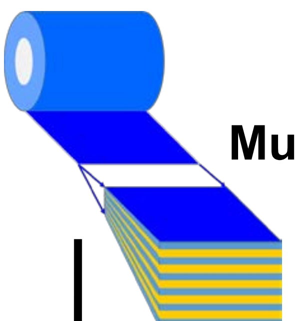
Relevance

Objective: To fabricate and scale up high temperature, high energy density, and low loss dielectric films for 500 μF to 1 mF capacitor manufacturing, using a multilayered co-extrusion processing.

State-of-the-art technology:
- BOPP 1 mF DC-link Capacitor costs $60/mF
- Use temperature = 105°C
- External cooling system



Multilayered Film

New class of Materials :
- High Temperature Use,
- Increased energy density
- Compact size
- Reduced cost

PEEM program DC-link Capacitor Target

Capacitance (μF)	>1000
Voltage rating (VDC)	650-900
Tanδ at 10 kHz	< 0.02
ESR (mΩ)	< 2
ESL (nH)	≤ 5
Temperature (°C)	**140**
Ripple current (A rms)	100
Failure mode	benign
Lifetime (hrs)	>20,000
Volume (L)	**≤ 0.6**
Cost (/mF)	**≤ $30**

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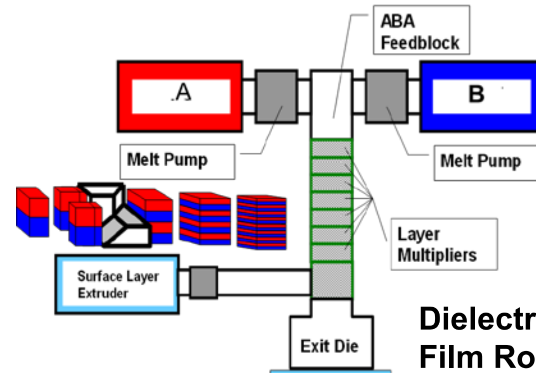
Milestones

Milestones	Status	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Multilayer film processing and optimization production scale up									
• Processing optimization	Year 1 - Complete								
• Production scale-up	Year 1 - Complete Year 2- In-progress								
Multilayer film thickness reduction									
• Film stretching	Year 1 – Complete								
• In-line processing (< 4 µm)	Year 2 - Complete								
New material development	In-progress								
Multilayer film metallization	In-progress								
Capacitor designing	Year 1 - Complete								
Capacitor fabrication and testing									
• 100 µF	Year 2 - Complete								
• 500 µF	Year 2 -In-progress								
Cost models	Year 2 - Complete								

Value Statement

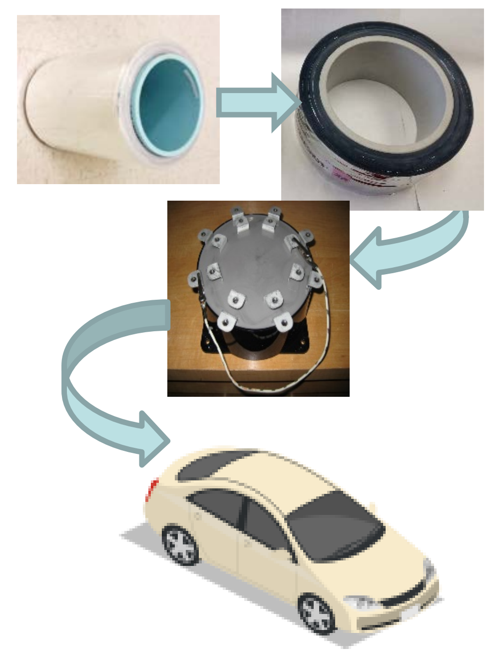
Dielectric multilayered films (MLF) technology enables up to a ***<u>½ reduction in capacitor volume</u>*** by replacing BOPP or Mylar *<u>while extending usage temperatures to 150 °C</u>*.

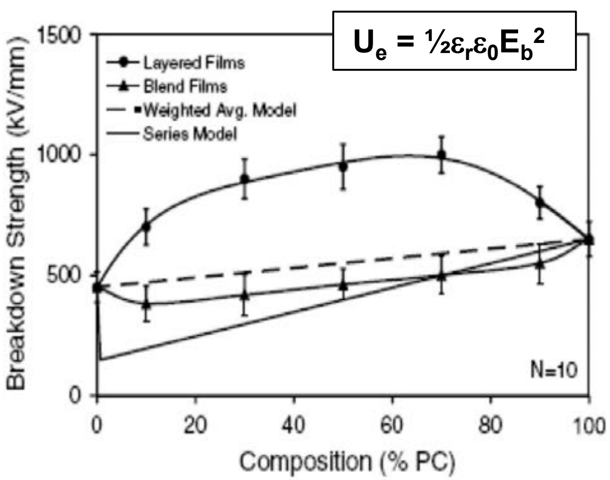


These advances were enabled by leveraging:

- Synergistic combination of high dielectric constant and high breakdown strength/low loss polymers in parallel layered construction
- Changing polymeric material failure mode to increase layered film breakdown strength

Dielectric Film Roll





Multilayer Film Properties

- Increased dielectric constant
- Increased temperature capability
- Improved Breakdown Strength
- Reduced Losses

Reduced Volume and Weight Capacitors

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Approach

Coextrude a high dielectric constant material with a high breakdown strength material to achieve improved dielectric properties in film and capacitor prototypes

Film Development

Polymer Resins → Nanolayer Film Coextrusion → Film production Scale-up →

Resins

Film Production

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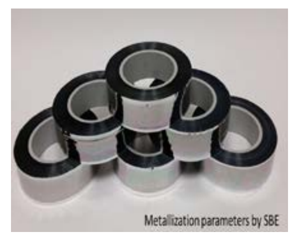
Capacitor Development

Film Metallization and Slitting → Film Winding and End-capping → Capacitor Fabrication and Testing



Metallization and capacitor Fabrication

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Materials Research → Capacitor Prototypes → Commercial Marketplace

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Approach – Film Development

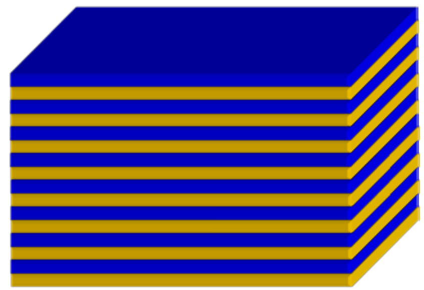
Coextrude a high dielectric constant material with a high breakdown strength polymers

Polymer A

Advantage: High dielectric constant

Disadvantage: High loss, high hysteresis, low breakdown strength, slow discharge time

Multilayer Film



A/B layer Structure

Polymer B

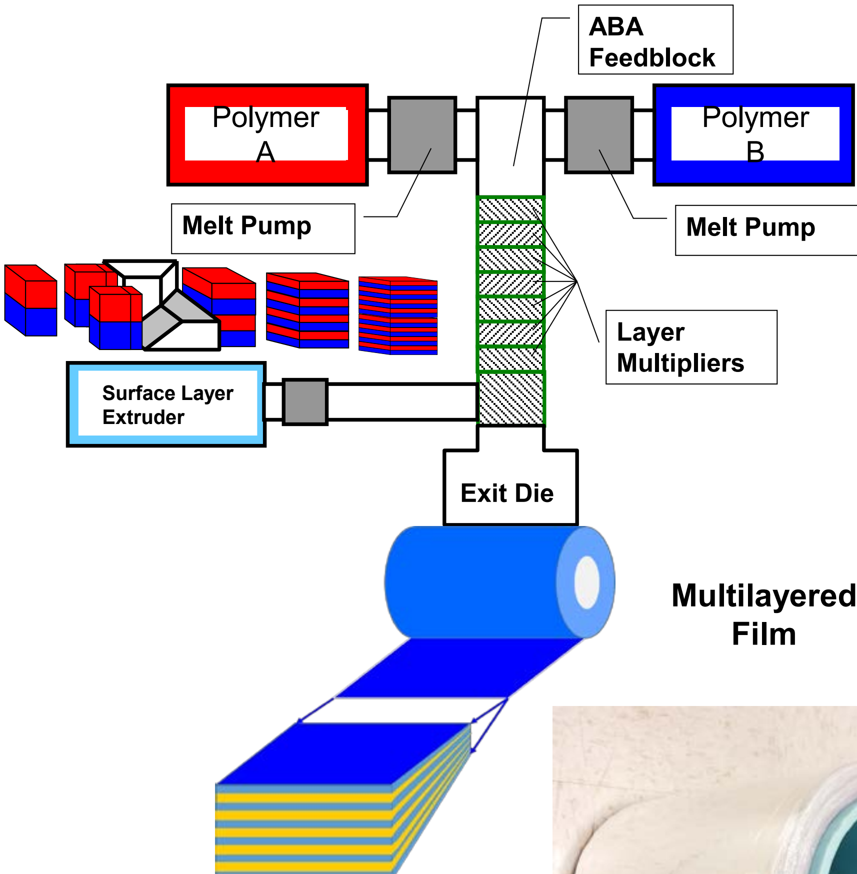
Advantage: High breakdown strength, low loss, low hysteresis, fast discharge time

Disadvantage: Low dielectric constant

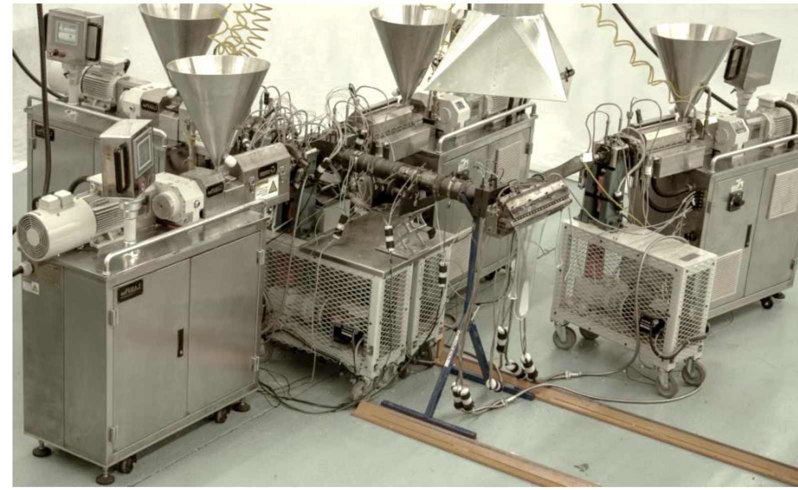
Optimize energy density and minimize dielectric loss by varying the number of layers, composition, layer thickness, and materials

- Increased Dielectric Constant : > 4.0
- High Dielectric Strength: > 1000 MV/m
- Increased Energy Density : 10 – 16 J/cc at film level
- Increased Temperature: 150 °C

Background- Coextrusion Process

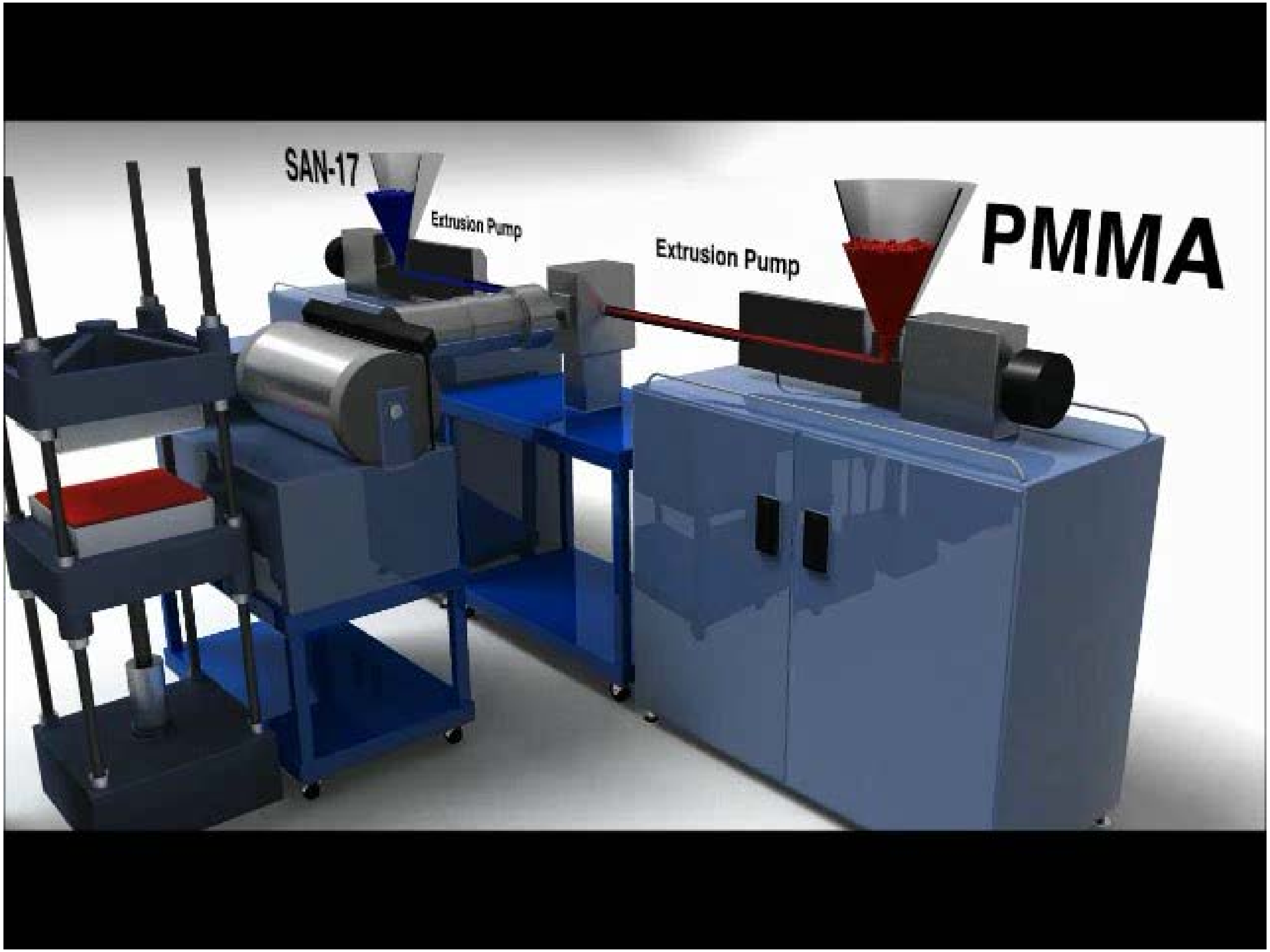


R&D Coextrusion Line



Pilot Coextrusion Line

Background- Coextrusion Process



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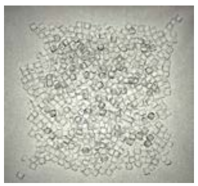
Technical Accomplishments

Film Processing Optimization

5
Resins

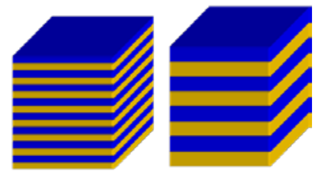


Resin A : 2
Resin B: 3

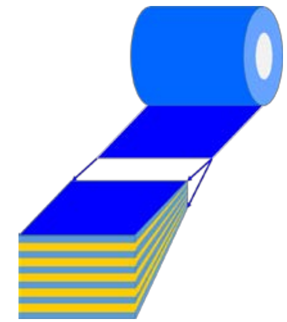
6+
Film thicknesses

15, 12, 9, 8, 6, 4, <4 μm

3
Number of layers



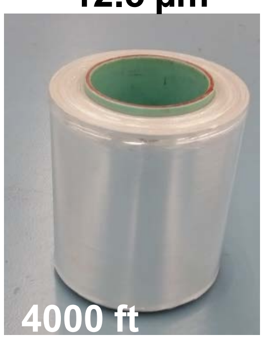
Small Rolls



layer/film thickness effect, layer thicknesses = 10s to 100s nm

Production Scale-up

12.5 μm



890±120 MV/m
Non-DOE

8.0 μm

975 ± 130 MV/m

4.5 μm

1250 ± 150 MV/m

3.5 μm

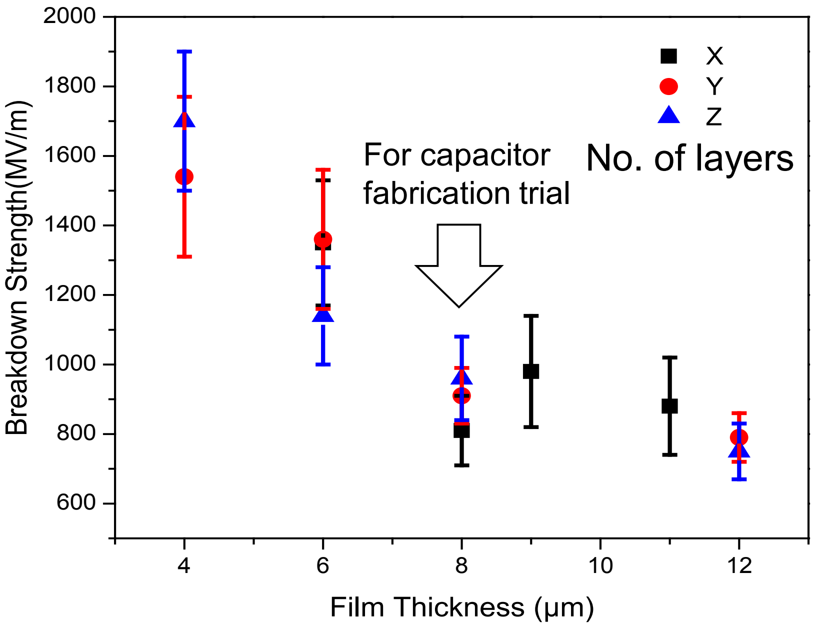
1400 ± 250 MV/m

- **Thickness:**
  12.5 to 3.5 μm
- **Quantity:**
  Several Rolls
  3000 -7000 ft./roll

Optimized film thickness = 8 μm

Technical Accomplishments

Breakdown Strength



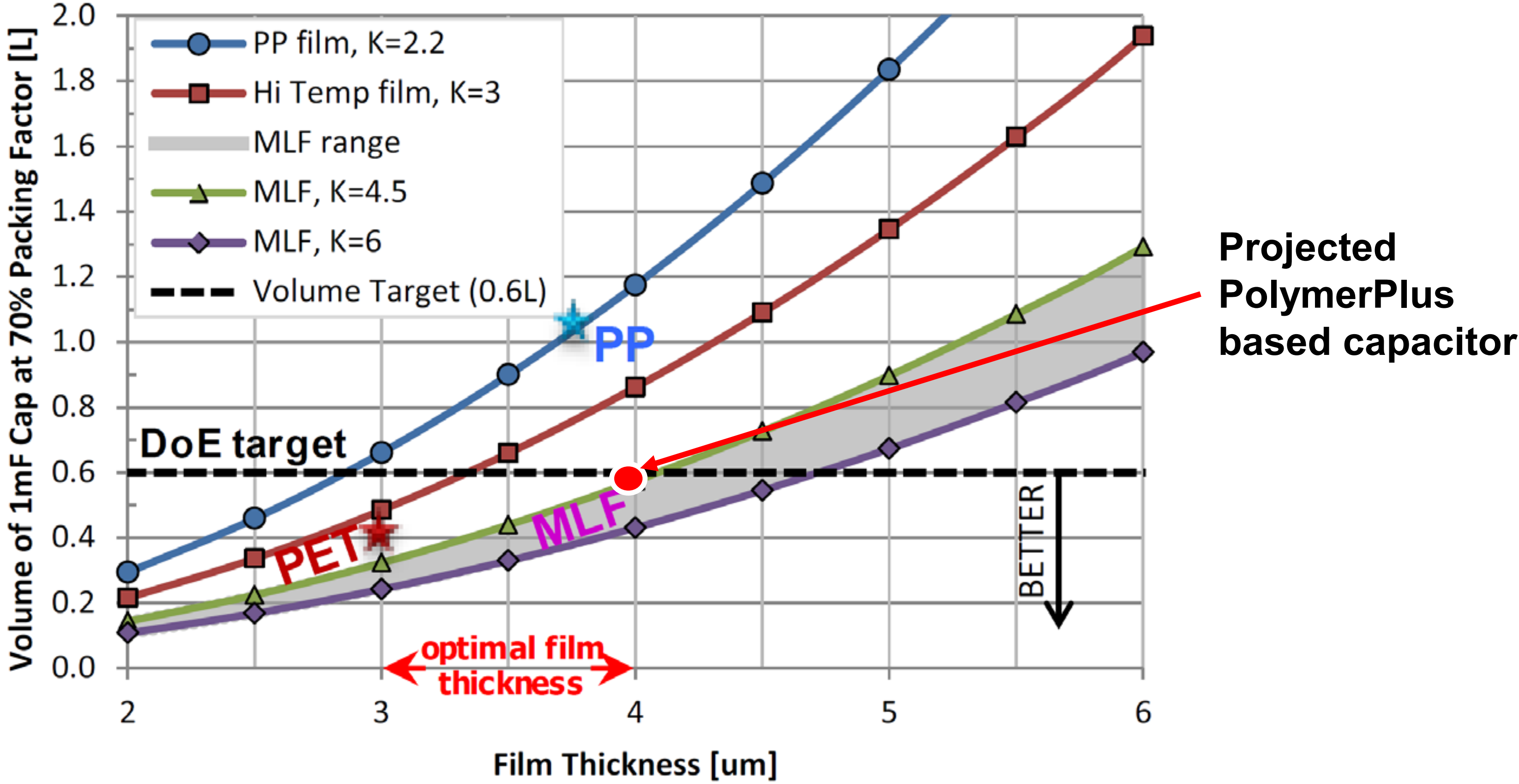
Properties	Multilayer Film	Commercial BOPP
Layers	10s	1
Composition	X/Y	100
Thickness, μm	12-4	3-4
Dielectric constant	4.0 (1 kHz)	2.25
Breakdown Strength (MV/m)	>1100	800
Temperature, °C	150	< 105
Tan δ	0.005	0.0003

- Multilayered films developed in DOE program showed 1.8X higher dielectric constant and more than 30% higher breakdown strength than commercial BOPP film.
- Dielectric constant can be increased using higher content of Resin A (high dielectric constant).

Using $U_e = \frac{1}{2}\varepsilon_r\varepsilon_0 E_b^2$, a **3X increase in energy density** is estimated.

Technical Accomplishments

Film Properties and Capacitor Size Correlation



Commercial BOPP and PET films = 4 µm, PolymerPlus Film Status = 3.5 µm

With existing formulations at 3.5 µm film thickness, a 40% capacitor size reduction is possible.

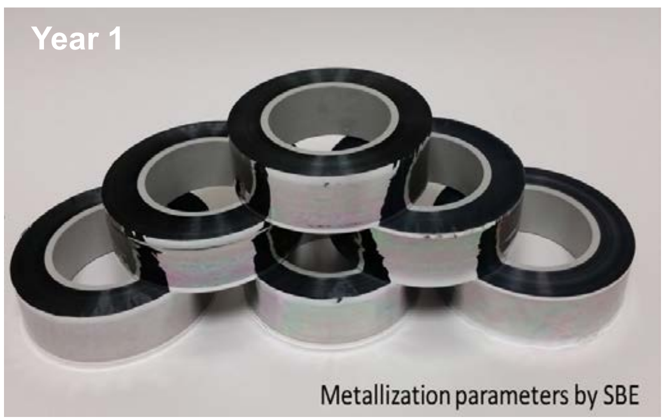
Technical Accomplishments

Film Metallization

Objective: To metallize HT-MLF film rolls for capacitor fabrication trials

Progress:

- Two metallization trials of 3000 ft HT-MLF film completed.
- One metallization trial of 7000 ft of MLF film completed.
- Additional trials are scheduled with 8 μm film.



8 μm film thickness

8 μm film thickness

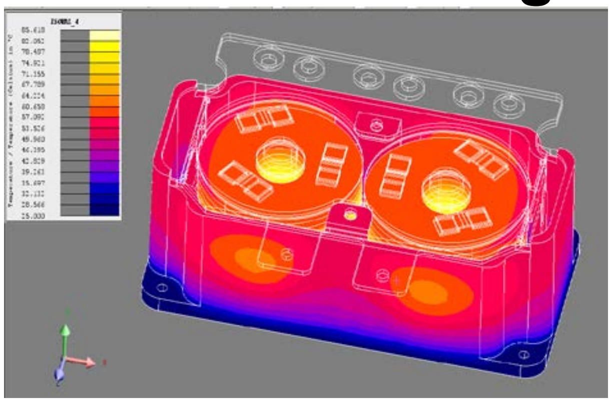
4.5 μm, Significant wrinkles

Metallization on existing BOPP metallization equipment demonstrated.
Improved film quality critical for better capacitor winding.

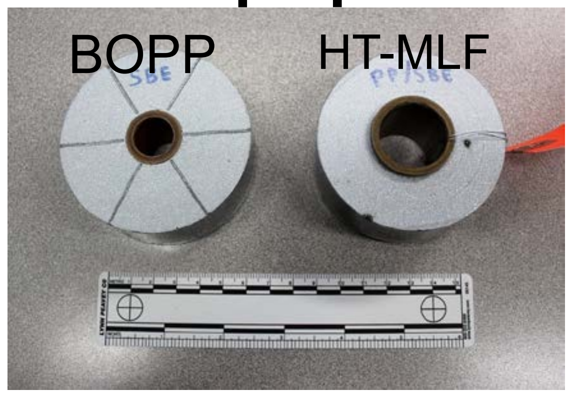
Technical Accomplishments

Capacitor Designing and Fabrication

3D modeling



25 µF parts



- A baseline using metallized PP film into a industrially relevant inverter was studied as a benchmark study..
- Performed iterative thermal and thermomechanical FEA to support overall capacitor design
- Comparison of rolled BOPP and HT-MLF Capacitors

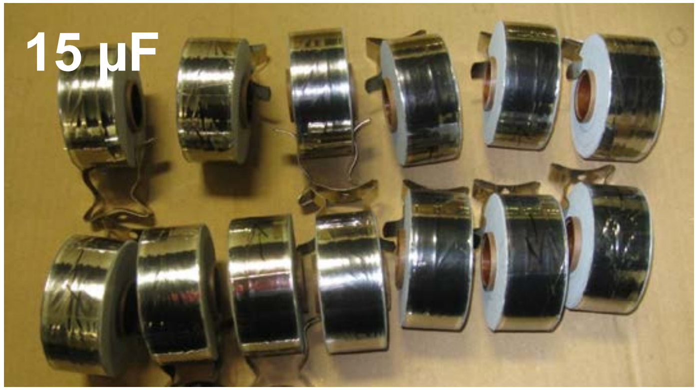
100 µF windings

Film Thickness : 8µm

- Several 25 µF and few 100 µF parts were fabricated in first year of the program.
- Low voltage stress and higher leakage currents were observed due to wrinkled metallized films.

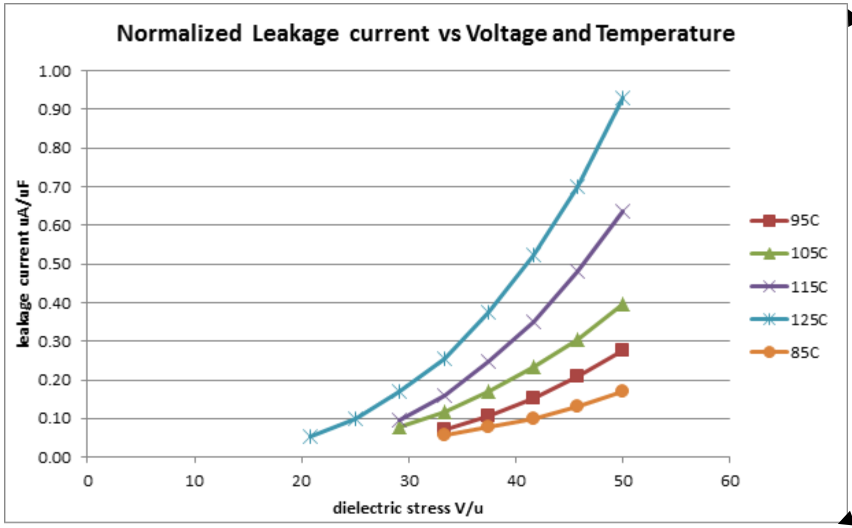
Technical Accomplishments

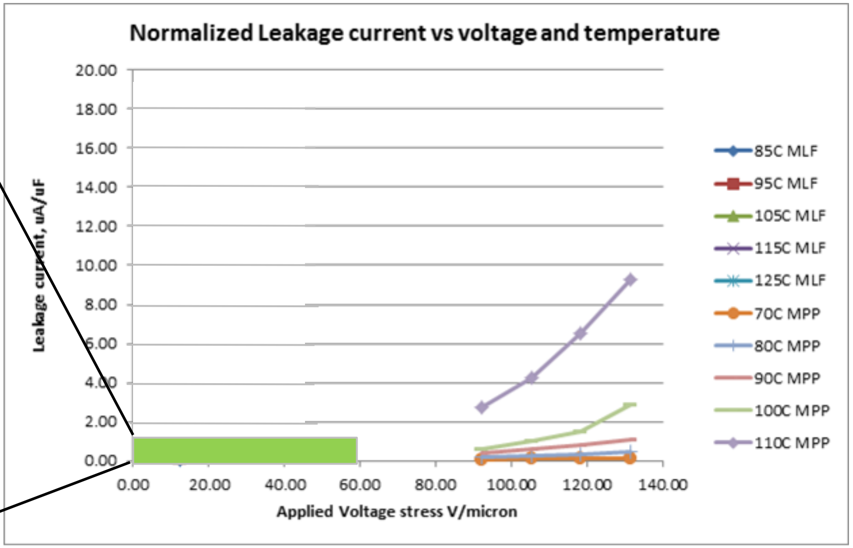
Leakage Current



Film Thickness : 12μm

- High Breakdown strength
- Lower leakage current
- Improved clearing

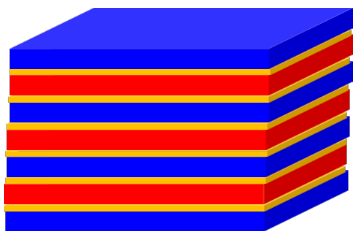


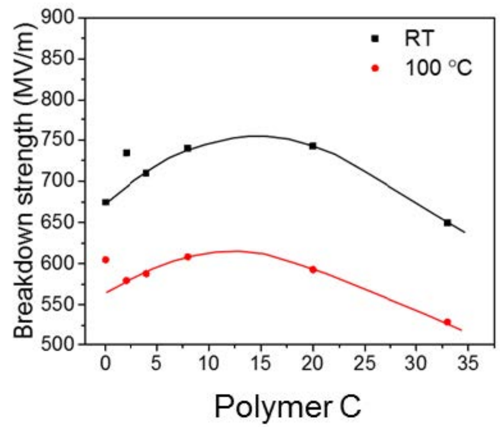


Technical Accomplishments

Multilayer film modifications

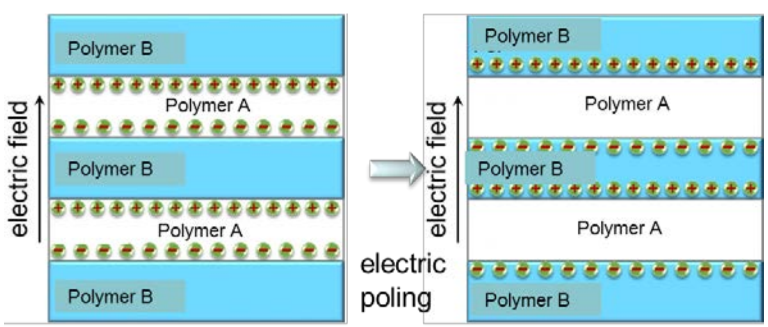
Adding 3rd polymer to modify layer-layer interface

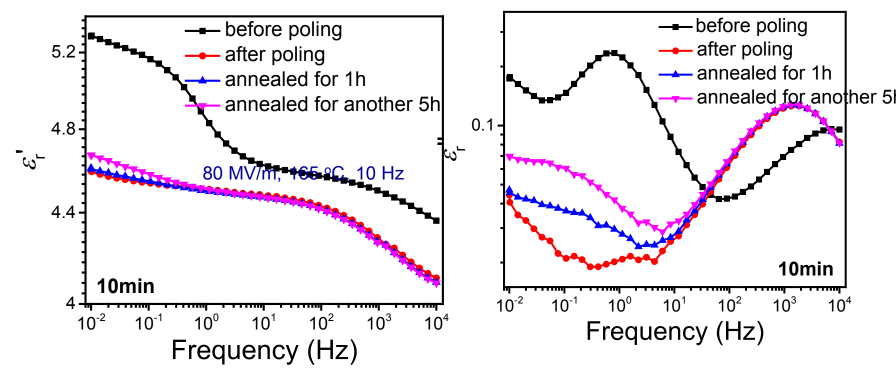




- Improvement in breakdown strength possible with addition of 3rd polymer.
- Modified layer-layer interface.

Reducing losses in high temperature MLFs





- Thermal annealing can reduce the impurity ions loss to some extent by regulating the crystalline structure of polymer A.
- Unipolar poling is an efficient way to drive impurity ions from polymer A into polymer B. Multilayer films are suitable for unipolar application such as DC-link capacitors in EVs.

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Responses to Previous Year Reviewers' Comments

This project is a new start.

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Collaboration and Coordination with Other Institutions

Partners/Collaborations

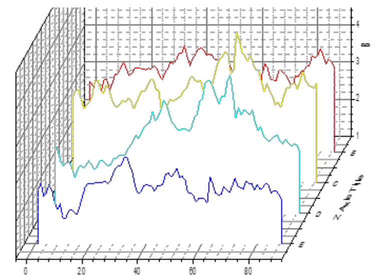
SBE	**Industry**	Project sub-contractor: Leads efforts to design, fabricate and test of capacitor prototypes ranging from 15-500 μF.
Oak Ridge National Laboratory	**National Laboratory**	Project sub-contractor: Leads efforts to designing, thermal and thermal-mechanical FEA analysis and cost modeling.
Case Western Reserve University, EST 1826, think beyond the possible	**University**	Project sub-contractor: Leads efforts understand material structure-properties, develop new materials

Remaining Challenges and Barriers

Improving film quality

Film Quality

Thickness Uniformity



Target Thickness deviation: <5%

- Film thickness uniformity critical in winding large capacitor parts with improved performance.
- Internal equipment upgrade completed, through internal development, to address this issue.

Production scale-up

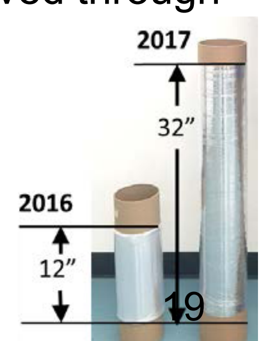
- Existing capability allows production of 25 lb. film rolls. Higher production will be required to fabricate several tens of parts.
- Increased production scale-up (several hundred lb.) of 12 µm film was achieved through manufacturing vendors.

Addressing Challenges: PolymerPlus Internal Development

- **40" Film Exit Die**
- **42" film take-off station**
- **In-line Thickness Gauge**

⇨

8 - 32" Wide film
10 – 150 fpm film collection speed
Reduced wrinkles



Increased production up to 75-150 lb./shift possible

Proposed Future Work

- Multilayer film production scale-up trials : ~ 10,000 ft x 12” x 8 μm
- Investigate 4 μm film thickness production to reduce wrinkles.
- Film Metallization trial – as per SBE design
- Capacitor fabrication : 25 μF to investigate effect of temperature
- Capacitor fabrication: 500 μF as deliverables
- Capacitor parts testing
- Continued work to develop approach to improve multilayer films – annealing
- Continued thermal and thermomechanical FEA

Any proposed future work is subject to change based on funding levels.

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Summary

Films

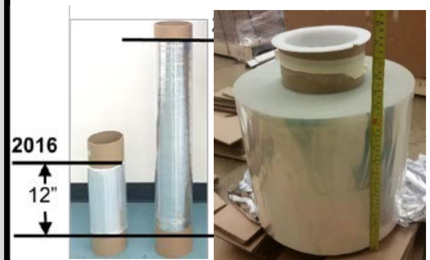
Film Optimization

Multilayer Films

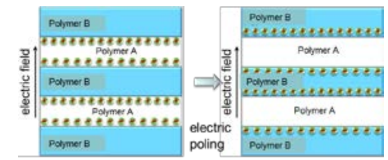
8, 4.5 μm

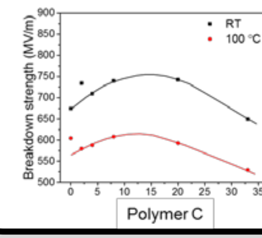
Film Production

- PolymerPlus
- Vendor



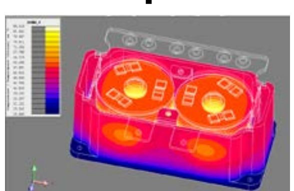
Material Advances





Capacitors

Capacitor Development



Metallization and Capacitor Parts

- Demonstrated use of commercial polymers for capacitor applications
- Demonstrated improved dielectric film performance
- Requires film quality improvement for better capacitor windings
- Multilayer film "drop-in" products feasible.